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Free Flight Simulation: An Initial Examination of Air-Ground Integration Issues

S. Lozito, A. McGann, P. Cashion, M. Dunbar, M. Mackintosh, V. Dulchinos, and K. Jordan
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Summary

The concept of "free flight" is intended to emphasize more flexibility for operators in the National Airspace System (RTCA, 1995). This may include the potential for aircraft self-separation. The purpose of this simulation was to begin examining some of the communication and procedural issues associated with self-separation in an integrated air-ground environment. Participants were 10 commercial U.S. flight crews who flew the B747-400 simulator and 10 Denver ARTCC controllers who monitored traffic in an ATC simulation. A prototypic airborne alerting logic and flight deck display features were designed to allow for increased traffic and maneuvering information. Eight different scenarios representing different conflict types were developed. The effects of traffic density (high and low) and different traffic convergence angles (obtuse, acute, and right) were assessed. Conflict detection times were found to be lower for the flight crews in low density compared to high density scenarios. For the controllers, an interaction between density and convergence angle was revealed. Analyses on the controller detection times found longer detection times in the obtuse high density compared to obtuse low density, as well as the shortest detection times in the high density acute angle condition. Maneuvering and communication events are summarized, and a discussion of future research issues is provided.

Introduction

Free flight is a new operational concept that emphasizes more flexibility for operators in the airspace system, as well as a more strategic management of airspace by the various users (e.g., pilots, controllers, dispatchers). Some of the goals for the free flight program include more system efficiency, more collaboration among air carriers and the air traffic system personnel, and pilot involvement in separation responsibility. To help define this concept and its viability, the RTCA has published a document defining some of the required technology, procedures, and progressive steps towards the goal of more user flexibility (RTCA, 1995).

Pilots, controllers, and dispatchers will be impacted by the technological and procedural changes that will accompany the transition towards free flight and the increased opportunities for aircraft self-separation (National Research Council, 1997). While it is important to note that the controller will retain final responsibility for separation, aircraft may be allowed more maneuvering flexibility, including increased opportunities for self-separation. Although there is debate surrounding these issues, the availability of self-separation will be affected dramatically by the communication, navigation, and surveillance (CNS) equipment for the ground and aircraft. Also, human factors performance parameters for system users must be considered and assessed to make the transition to Free Flight feasible.

Several recommendations and assumptions are provided by the RTCA to allow for early free flight implementation, especially those associated with the tasks related to increased opportunities for operational flexibility. Many of these assumptions pertain to technology and procedural changes in airspace operations.

Communication/surveillance

Free Flight will require an increase in aircraft navigation and surveillance to aid the task of self-separation. A possible solution suggested by many in the aviation community is Automatic Dependent Surveillance (ADS) technology. The ADS System is a service by which aircraft transmit, via data link, information derived from onboard navigation systems (RTCA, 1992). These data include, at a minimum, three-dimensional position of the aircraft. The capabilities of ADS also may provide a means for data transmission to enable aircraft self-separation in certain environments.

Conflict alerting logic/cockpit display of traffic information (CDTI)

In addition to the increase in CNS data, some tools associated with automated conflict detection need to accompany the transition to more flexible airspace operations (RTCA, 1995; Paielli & Erzberger, 1997; Yang & Kuchar, 1997). The tools will need to be both ground-based and aircraft-based to permit conflict detection and resolution for the controllers and pilots. (Although this research considers both pilot and controller human performance data, the simulation environment and general design allowed for a greater emphasis on flight crew data. Thus, the controller conflict prediction tool will not be discussed in this paper.) For the aircraft, the conflict logic will need to exchange data with other surrounding aircraft, possibly using a broadcast capability of the ADS function (ADS-B). Data could then be exchanged in an automatic fashion at a rapid rate, transmitting and receiving aircraft performance parameters with aircraft that are similarly equipped. One prototype of aircraft alerting logic has been developed by researchers at the Massachusetts Institute of Technology (Yang & Kuchar, 1997).

The concept of airspace zones associated with individual aircraft is also suggested as a means to accomplish progress towards a free flight implementation. These zones around aircraft would be represented in the airborne alerting logic to help determine the probability of conflict. Similar to the concept of aircraft zones represented in Traffic Alert and Collision Avoidance System (TCAS) logic, a system currently available on many aircraft designed for collision avoidance, these additional zones would define regions around aircraft that serve as a buffer for collision protection. There are two zones discussed in the free flight concept implementation: the protected zone and alert zone (RTCA, 1995). The protected zone is a representation of the current operational separation standards that exist in the domestic enroute airspace. In the domestic United States, five nautical mile (nm) lateral separation or one or two thousand feet vertical separation between aircraft is required in the enroute environment, with the vertical separation varying depending on the altitude of the operations. For the purposes of future requirements and technological advancement, it is assumed that one thousand feet vertical separation will soon be adequate for most of the enroute altitudes. This will be the only predicted modification to the existing separation standards. The protected zone, therefore, is expected to remain free of other aircraft.

The alert zone is a more unique conceptual space associated with free flight and will also be defined around an aircraft. It must be larger than the protected zone, as it is intended to permit a preview of potential traffic situations, and to allow for worst-case human and systemic responses (RTCA, 1995). The definition of this zone will be influenced by aircraft equipage and performance characteristics as well as by human performance activities associated with aircraft self-separation. Due to the nature of these parameters, the alert zone will be a time-based zone rather than a distance-based zone. A comprehensive identification and definition of required human performance parameters based on self-separation tasks is not yet available; therefore, the alert zone is not yet thoroughly defined.

In addition to new conceptual airspace and conflict detection tools, the data generated by the conflict logic will require an aircraft display for the depiction of the relevant traffic and conflict information. The flight deck display should be able to portray traffic within the range of the ADS-B capability. This display will assist the pilots in the identification and evaluation of traffic and in the assessment of maneuvering options. Several studies have recently been conducted to assess new display systems (Johnson et al., 1997; Johnson, Battiste, & Holland, 1999) as well as to assess information display requirments, such as levels of intent information on the flight deck (Barhydt & Hansman, 1997; Cashion & Lozito, 1999). In combination, the potential for increased CNS data, the airborne alerting logic, and the aircraft traffic display may enable an increase in user flexibility in maintaining self-separation under certain conditions.

Previous flight deck experiments

In an attempt to begin exploration of these issues, two simulations were conducted at NASA Ames Research Center. The first simulation was designed primarily to explore early development and procedural concerns of the free flight concept. An attempt was made at defining and developing some of the technology and procedural assumptions for aircraft self-separation.

There has been some speculation that the pilot task of self-separation may be negatively affected by the amount of other aircraft (traffic density) in a given airspace. After participating in the demonstration, the participants were asked to provide feedback about the task of self-separation and the associated workload. Most of the flight crew participants did not feel that the task of self-separation (as portrayed in the demonstration) represented high workload. Many suggested that if there was an increase in traffic density in the relevant airspace, their workload may increase dramatically. However, research by van Gent, Hoekstra, and Ruigrok (1998) revealed that subjective ratings from flight crews participating in self-separation tasks do not report an increase in workload or a decrease in safety as a function of traffic density.

After conducting an initial simulation to test the overall feasibility of self-separation in a simulation environment, a second simulation allowing a more systematic examination of some of the flight deck human factors parameters was conducted (Cashion, Mackintosh, McGann & Lozito, 1997; Mackintosh et al., 1998). There were several concepts expressed in the early description of free flight (RTCA, 1995) that were used in this investigation. These included ADS-B data assumptions, the development of a prototypic airborne alert logic (Yang and Kuchar, 1997), and the development of a prototypic aircraft display of traffic (Johnson et al. ,1997). Of specific interest were the effects of traffic density and the application of Visual Flight Rule (VFR) right-of-way rules to the self-separation tasks. Commercial airline pilots flew eight different scenarios reflecting high and low traffic density and varying convergence angles. The participants were provided with airborne alerting logic designed to provide early information about potential conflicts. In addition, a CDTI was provided to display the alert information to the flight crew participants. While there were interesting findings related to VFR right-of-way rules and their application, there were very few results indicating traffic density differences. (For a description of this study and its results see Cashion et al., 1997).

Controller factors

While our earlier investigations have not included an examination of controller human factors concerns, there has been other research conducted in the area of free flight and controllers. Most of these studies have tended to focus on the impact of free flight flexibility upon the controller's workload or situation awareness, though additional work has been done on controller information requirements in free flight (Duley, Galster & Parasuraman, 1999) and the use of controller conflict detection aids in free flight (Castaño & Parasuraman, 1999). An investigation by Endsley (1997) revealed that free flight leads to a reduction of controller situation awareness. Others have found that controller workload increased as aircraft operate more independently (Hilburn, Jorna, Byrne & Parasuraman, 1997; Fleming, Lane, & Corker, in press). Traffic density has also been considered when examining controller performance in a free flight environment. Much of the work related to the concept of dynamic density metrics, a method to indicate controller workload, assumes traffic density as a significant contributor to that workload parameter (Wyndemere, 1996; Laudeman, Shelden, Branstrom, & Brasil, 1998). An increase in traffic density was also associated with an increase in controller physiological workload (Hilburn, Jorna, et al., 1997), longer conflict detection times (Galster, Duley, Masalonis & Parasuraman, 1998; Castaño & Parasuraman, 1999), significantly longer reaction times to handoffs (Galster et al., 1998), and more operational errors (Galster et al., 1998). Similarly, the research by Endsley (1997) found that higher traffic density led to reductions in controller situation awareness.

In addition to concerns about traffic density and controller performance, it also has been suggested that various angles of convergence may differentially affect the task of the controlling traffic. When comparing large and small convergence angles, Remington, Johnston, Ruthruff, Romera, and Gold (in press) found that for controllers larger angles lead to longer detection times compared to smaller angles. In a report discussing air traffic control (ATC) complexity, Wyndemere (1996) also suggests the detection of conflicts by controllers may be impacted by the size of the conflict angle. Wyndemere reports that shallow angles may lead to longer monitoring times for the conflict, as well as create difficulties in conflict resolution. Hence, convergence angles may impact on the complexity of the controller task.

Current study

The purpose of this full-mission simulation was to begin examining some of the flight crew and controller human performance issues in a self-separation environment. This study was not intended to be a systematic assessment of display features for self-separation. (For research in that area see Johnson et al., 1997; Johnson et al., 1999) Particular emphasis was given to the communication and maneuvering procedures represented with the implementation of free flight. This research was conducted to assess of some of these procedural and communication issues, with the goal of providing timing data that may be relevant to the development of some of the new technologies (e.g., ground-based and airborne alerting schemes). Additionally, traffic density and conflict angle were studied in an attempt to assess what impact these factors may have on controller and pilot human performance parameters when considered in a free flight operational context.

Method

Participants

Participants were run in groups consisting of one controller and one two-person flight crew per group.

Flight crews

Participants were ten flight crews, consisting of both captains and first officers from a major US airline. Each member flew in their normal crew position. All crew members were either current on the B747-400, or retired for not more than six months. Flight crew participants had a mean total flight time of 18,400 hours and a mean total flight time on the B747-400 of 1,820 hours.

Controllers

Ten full performance level controllers from the Denver Air Radar Traffic Control Center (ZDV) participated in this study. All controllers were current on the sector under study. Controller participants had means of 13.3 years experience as controllers and 5.8 years of experience as full performance level controllers at ZDV.

Simulation Facilities

There were two simulation facilities used in this simulation experiment. The Boeing 747-400 (B747-400) Simulator was utilized for the simulation of the aircraft environment, while the Airspace Operations Laboratory was used to simulate the ATC environment. Each of these facilities located at NASA Ames Research Center will be described briefly, with references indicating sources for more information on the simulators.

NASA B747-400 Simulator

The NASA B747-400 Simulator was built by CAE Electronics and is certified to the FAA Level D certification requirements (Sullivan & Soukup, 1996). The visual system uses photo texturing and offers superior scene quality, depicting out the window scenes in either night, day, dusk, or dawn conditions. In addition, the simulator has an advanced digital control loading and six degree-of-freedom motion system. Advanced avionics on the B747-400 simulator includes two flight management computers (FMCs), three multi-function control display units (MCDUs), a Ground Proximity Warming System Unit, and an ARINC Communications, Addressing, and Reporting System (ACARS) Management Unit. Data collection is available for user interaction with all subsystems, including the autopilot system and communication devices. (For a more detailed description of the aircraft simulation facility, see Sullivan and Soukup, 1996).

Airspace Operations Laboratory

The Airspace Operation Human Factors Laboratory is implemented at the part-task level with broad coverage of the airspace system (Pisanich, Lee, & Kaneshige, 1997). This laboratory has the capability to portray airspace regions in a realistic environment, including display tools and functions present in current ATC facilities. It is capable of supporting experiments planned with other high fidelity simulations, such as the B747-400 simulator, by maintaining network and software links. Unique technologies for this laboratory include near real-time data analyses and high fidelity ATC workstations. Computers and software have the capability to be configured as ATC displays, flight deck workstations, or support stations, as required by the experiment.

The laboratory consisted of 12 SGI Indy R5000 computers and a Challenge server that could be configured either as ATC sector stations or as multiple single pilot flight deck workstations. As ATC sector stations, these systems could be networked through a link with the simulation facility or as standalone systems. Two SGI Indigo workstations were available for development or as experiment coordination systems. The laboratory also contained a cluster of ten Sun Ultra computers that support the advanced air traffic control system CTAS (Center TRACON Automation System, see Erzberger, 1992) and pseudo aircraft generation and control tools (PAS). (For a more detailed description of the Airspace Operations Laboratory, see Pisanich et al., 1997.)

Design

Each flight crew and controller group participated in a series of eight experimental scenarios, which were varied by traffic density and conflict angle. There were two levels of traffic density: low (7 to 8 aircraft) and high (15 to 16 aircraft). Traffic density levels were equivalent on both the controller's and flight crew's traffic displays. Within each traffic density, participants were exposed to four scenario types. In three scenarios, lateral conflicts were created by varying the intercept angle between flight crew's aircraft (ownship) and an intruder aircraft (acute, right, and obtuse angles). In the fourth scenario, an aircraft passed close to the ownship, (8-9 nm), but did not trigger the alerting logic (Almost Intruder or AI scenario).

Alerting Logic

This study included a prototypic, airborne alerting logic designed to aid in airborne self-separation (see Yang & Kuchar, 1997, for a complete description of the alerting logic). This alerting logic overlaid the simulator's TCAS logic. TCAS involves immediate tactical conflict avoidance whereas the new airborne alerting logic was designed to help

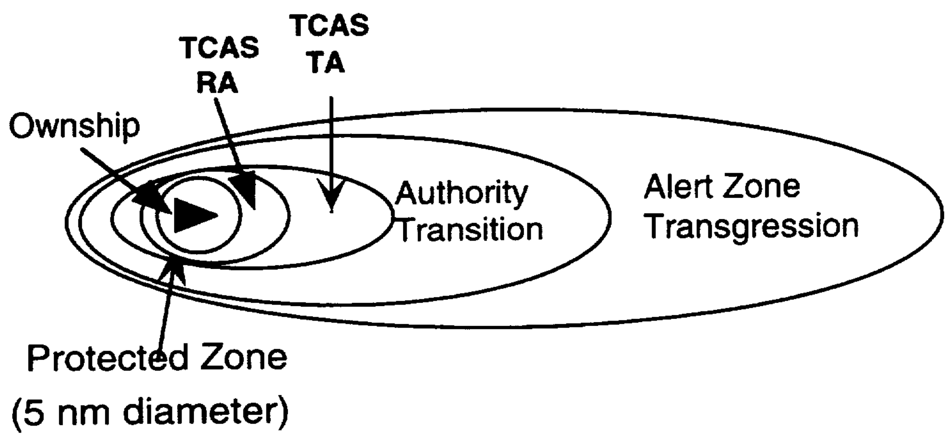

Figure 1. Relationship of new airborne alerting logic to TCAS logic.

crews manage the more strategic self-separation task. The goal was to create a seamless relationship between the airborne alerting logic and TCAS (see Figure 1). Therefore, TCAS was left intact with the exception that the first two threat levels of display symbology (unfilled diamond and filled diamond) were replaced with the experimental display symbology. The yellow circle for a Traffic Advisory (TA) and a red square for a Resolution Advisory (RA) were still available. Currently, the TCAS display depicts surrounding traffic up to 40 nm from the ownship on the navigation display. In contrast, the alerting logic in this study extended traffic depiction out to 120 nm in front of and to each side of the ownship and 30 nm behind the ownship based on the expected ADS-B surveillance capabilities (RTCA, 1992). To reduce clutter, an altitude filter limited the vertical range of viewable traffic to 4100 feet above and below the ownship.

The airborne alerting logic provided two additional alerting zones beyond that of TCAS. The earliest level of alerting was provided to the flight crews. An "alert zone transgression" (AZT) was triggered for the flight crews when the alerting logic predicted a pending violation of the protected zones of the aircraft (see Yang & Kuchar, 1997). Operationally, AZT was the point at which intervention may be required (RTCA, 1995).

There was no ground-based alerting logic represented in this study. Because of the absence of a ground-based probe, controllers were provided with minimal conflict alerting information derived from the airborne alerting logic. If no evasive maneuvers were taken after AZT, the Authority Transition point was reached. The Authority Transition point represented an increased threat beyond AZT and was visible only to the controller. At this point, the controller could take whatever action he/she thought was necessary to maintain aircraft separation, including canceling free flight on one or both conflicting aircraft.

Flight Crew Displays and Tools

Traffic was represented on the flight deck navigation display by the symbol "V" with the apex indicating the aircraft direction. Altitude (relative to ownship or absolute altitude) along with the callsign were displayed next to each traffic symbol. All traffic was initialized as non-threat aircraft. Figure 2 depicts a low density scenario with all aircraft in a non-threat status.

When the probability of a violation of the protected zone increased, an AZT was indicated to the flight crew by the following changes: 1) A blue line extending from both

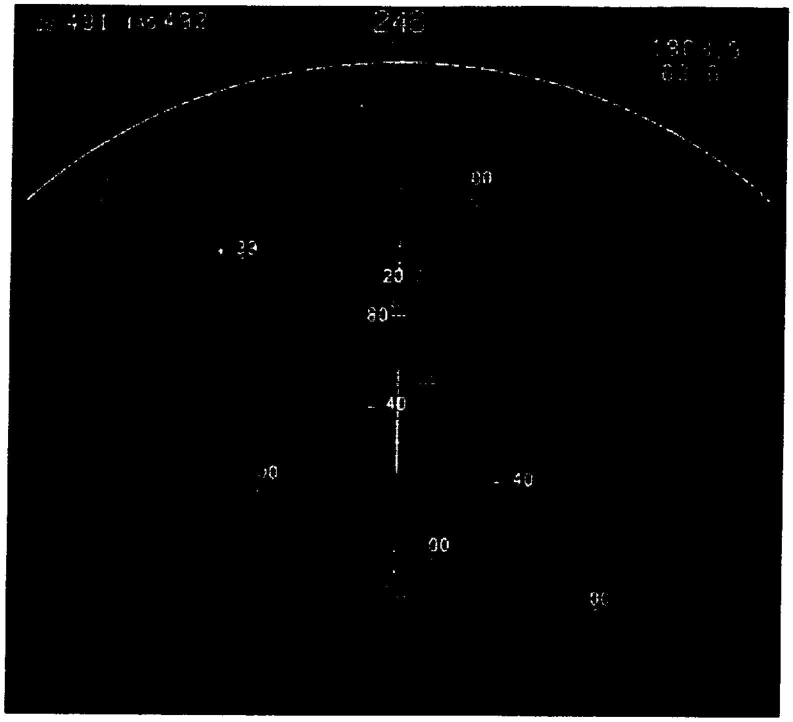

Figure 2. Flight crew's traffic display depicting non-threat aircraft.

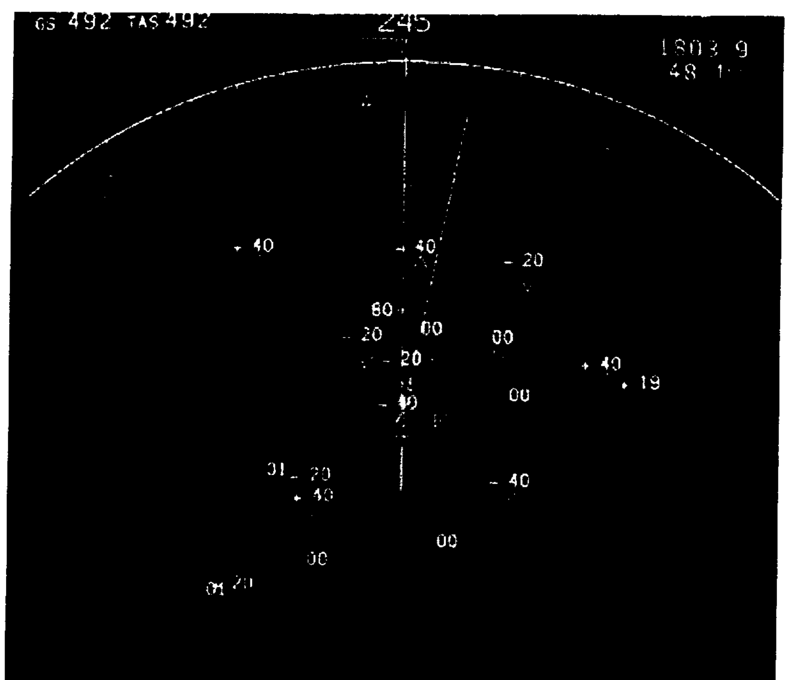

Figure 3. Flight crew's traffic display depicting an Alert Zone Transgression (AZT).

the ownship and the intruder aircraft symbols. At the end of each line was a blue circle that represented the current separation standard of 5 nm in diameter. Any overlap of the circles indicated impending loss of lateral operational separation; 2) An aural warning "Alert" sounded twice; 3) The word "ALERT" appeared in blue on the lower right hand corner of the display, along with the intruder's call sign, and the time to closest point of approach. The time to closest point of approach was the time remaining before aircraft were projected to pass in closest proximity to each other on current flight paths. All display features associated with the aircraft involved in an AZT (aircraft symbol, altitude readout, and callsigns) as well as the display changes related to an AZT appeared in blue to help identify which aircraft were predicted to conflict. Figure 3 illustrates the display changes associated with an AZT. As crews solved a conflict, the alert level degraded from an AZT to a non-threat status as the threat probability was reduced.

Flight crews also could select certain display features designed to aid them in self-separation. Selectable display features could be manipulated by a small box mounted above the Mode Control Panel (see Figure 4). Crews could reduce clutter by toggling a button to de-select the traffic callsigns. Another selectable feature was the temporal predictor. The predictor provided crews with an estimation, based on current aircraft state information, of where other aircraft would be relative to the ownship up to ten minutes into the future. The selection knob for the temporal predictors allowed crews continuous control of the predictor length from zero to ten minutes at one second intervals. With the predictors, crews could determine which aircraft might create a potential conflict prior to an alert level indication. When predictors were selected, they were displayed for all aircraft (see Figure 5). The predictor symbol was identical to the shape of the AZT symbology with a line and a circle that represented 5 nm in diameter, except that the predictor symbology was white while the AZT symbology was blue. Selected predictor time was displayed at the lower right hand corner of the navigation display. Also, to reduce clutter, predictors and callsigns of the non-conflicting traffic were automatically cleared from the display at AZT but could be reselected at any time. Finally, crew members could also de-clutter the navigation display by changing the horizontal map range. Ranges available were the same as those available on the navigation display on most B747-400 aircraft (10, 20, 40, 80, 160, 320, and 640 nm).

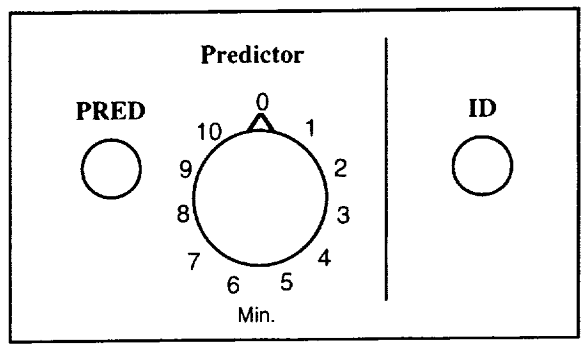

Figure 4. Control box for pilot selectable features.

Controller Displays and Tools

The display the controllers used during this study had similar features to those available on their current radar display (see Figure 6). The primary sector of concern for this study was Sector Nine in Denver Center (ZDV), which consists of overflight aircraft that are transitioning through the facility as well as aircraft that are arrivals into Denver International Airport. The airspace display included sector number, boundary lines for the sectors, and aircraft. Paper flight strips were not available for these participants; therefore, some information that would normally be provided on the flight strips was located on the data block. Additional flight strip information, such as the filed flight plan, and present heading for overflight traffic and metering fix and runway assignment for arrival traffic, also could be accessed by

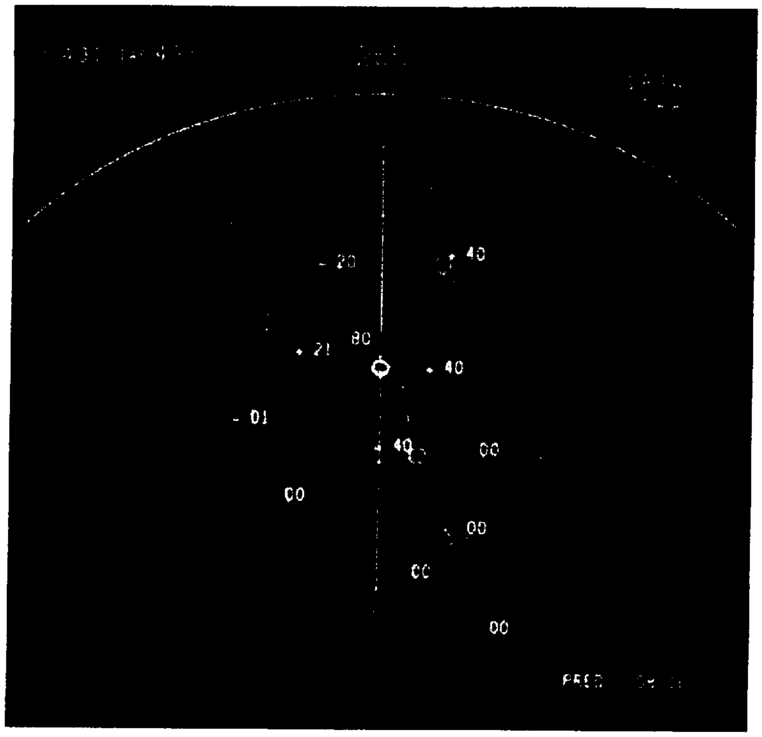

Figure 5. Flight crew traffic display with temporal predictors set at 8:16.

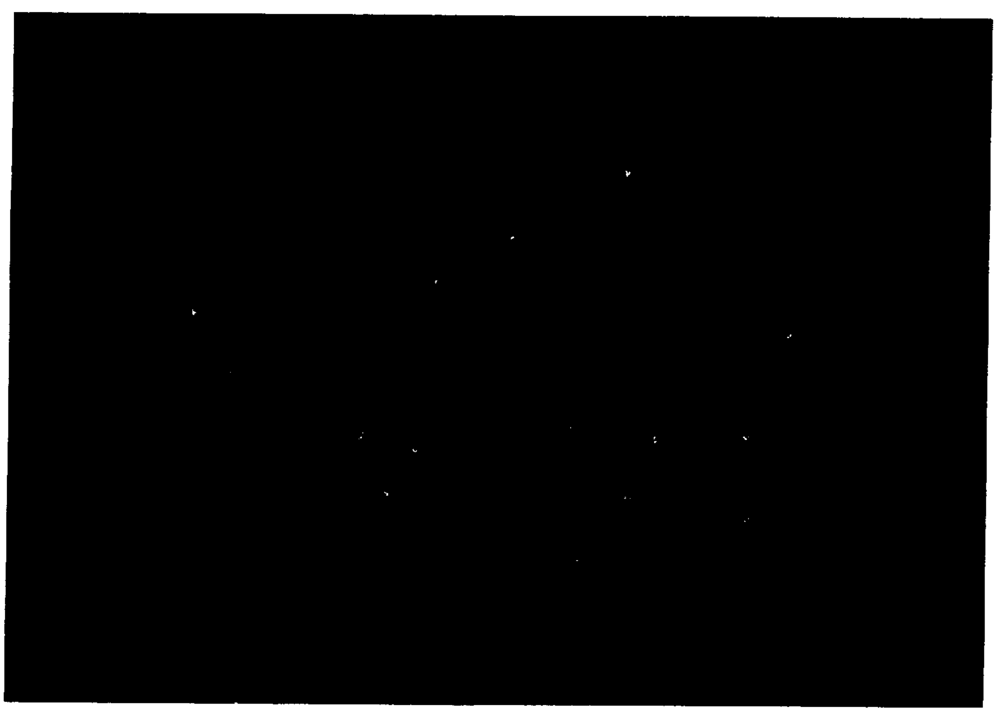

Figure 6. Controller's traffic display with vector lines selected at 2 min and a minimum separation ring for DAL152.

clicking on each aircraft. Electronic flight strips provided controllers with additional flight plan information, such as aircraft . The symbol for the aircraft was a diamond. Each aircraft had a data block containing information about the characteristics of that flight. The information contained in the data block was as follows: The aircraft call sign, the altitude plus a Mode C indication for altitude source, aircraft type with an alphanumeric indication of navigation equipment onboard, and airspeed. A leader line connected the data block to the aircraft symbol on the display. Additionally, although most of the display has white features portrayed on a black background, the color green was used for the symbol and data blocks of arrival aircraft to distinguish them from the overflight aircraft that were transitioning through the airspace.

The controller participants also had some additional features intended to help them manage the airspace. Many of these are used frequently by the controllers while working traffic at ZDV. The controller interface for these tools was primarily through the use of a trackball and keyboard. The trackball was typically used to select the aircraft and the keyboard was used to bring up a particular feature. The tools included an ability to zoom the display in and out, or move the center of the display to provide another view. In addition, a graphical representation of an aircraft's route information could be depicted. Navigation aids were also available on the display. Vector or trend lines were provided that would project where an aircraft would be laterally in increments of either one, two, four, or eight minutes. This was depicted as a line projecting from the aircraft symbol, and could be selected for as many aircraft as the controller desired. There was a capability to measure distances between any two graphical objects on the radar scope (e.g., measuring the distance from one aircraft to another). Finally, minimum separation rings were available to the controller to select for any number of aircraft. The separation rings was a ring representing a five mile radius around the aircraft symbol (five miles is the minimum lateral separation requirement in this environment). Controllers could use these rings as an indication of proximity of surrounding aircraft, or as a label function for an aircraft that may have had an unusual characteristic associated with it (e.g., an aircraft heading in the wrong direction of flight for that airspace).

An interface feature was added for this study that recorded the time at which controllers detected traffic conflicts. Using the trackball and keyboard, the controller participant was asked to select any aircraft that he/she thought might have required more attention due to a potential conflict. The participant would first select the "d" key on the keyboard, then select the aircraft that were involved in the conflict. The use of this interface on the part of the controller allowed us to collect objective conflict detection time data.

There was also a unique display feature added to facilitate the controller intervention procedure for this experiment. When the Authority Transition Point was reached, the controller was alerted in the upper right hand corner of the display with the flashing text *Alert Level 4*, along with the ownship aircraft's call sign. (Due to the nature of the scenarios, the conflict always involved the ownship aircraft.) The controller was instructed that at the onset of this alert, he/she should query the flight crews about their intentions and cancel free flight if necessary.

Procedure/Task

Flight crews and controllers were briefed jointly about the general goals of the free flight concept and the study, emphasizing the potential for increased operational flexibility and efficiency with free flight. Although the new display features and alerting logic were primarily used by the flight crews, pilots and controllers were briefed on these features and how they might be used on the flight deck. They were briefed that the new display features were designed to help the pilots assess situations, but they were not instructed as to specific operational requirements (e.g., maneuvering or contacting ATC) based on the alert condition. Any maneuvering or communicating was at the discretion of the crew. If a maneuver was necessary, the crews were told that they could maneuver and change any of their flight parameters at any point during the flight, but to keep fuel efficiency and time to destination in mind. Participants were informed that all aircraft in their vicinity had similar equipage and were on the same frequency and that ATC was also on the same frequency. They were informed that communication was available between any two aircraft or with ATC, but they were never specifically required to communicate with other flight crews or controllers. Finally, they were advised that the controller could intervene at the Authority Transition point and that the controller still retained ultimate separation responsibility.

The participants were informed that the flight crews would fly eight cruise segments from a starting point over Denver Center airspace toward one of two destinations, John F. Kennedy International (JFK) or San Francisco International (SFO) airports. Prior to the start of each run, the crews were asked to enter a flight management system (FMS) route that included departure airport, two waypoints and a destination airport. The crews were positioned at the optimum altitude and airspeed for their current gross weight, and no winds or turbulence were present. Although crews were told the scenarios' approximate duration, they were instructed to assume that they were going to arrive at their destination (JFK or SFO). Also, the flight crew participants were instructed that the separation standards required in the simulation were similar to those in enroute domestic flight: 5 (nm) laterally, and/or two thousand feet vertically.

After the briefing, flight crews and controllers were trained separately in the respective simulation environments. The training scenarios were different from the actual experimental scenarios, and were intended to expose the participants to different conflict convergence angles along with differing levels of traffic density.

Crews received approximately one and a half hours of training in the B747-400 simulator. The training involved flying four scenarios, each with a different type of conflict. It also included a discussion of the display features, rules of the road, and other task components. It was emphasized that crews could use the display features and communicate with ground and other aircraft as they deemed appropriate for this task. The pilot participants were requested to "practice" all the tasks associated with the use of the display features, as well as to contact other aircraft and the controller when necessary. One of the training scenarios continued to an Authority Transition point, which was the point at which the controller could intervene. Thus, the crews were provided with a sense of the timing parameters associated with the alert, and had an opportunity to hear the procedure the controller would use when intervention occurred (query first, followed by a cancellation of free flight if necessary).

Controllers were also trained for approximately one and a half hours. Their training consisted of monitoring three different scenarios. During their training session, the controller participants had an opportunity to use all of the interface tools provided in this study as well as to get accustomed to the Free Flight communications. They also participated in a scenario where the Authority Transition point, or controller intervention point, was reached to familiarize them with the timing and nature of the procedure.

Rules of the Road

According to the RTCA recommendations, the crews were instructed to determine who should maneuver according to the current VFR rules of the road (ASA, 1997). The relevant rule in this study states that when two aircraft are converging laterally the aircraft on the right has the right-of-way and the aircraft on the left should maneuver. Additional VFR rules are 1) when one aircraft is overtaking another, the aircraft being overtaken has the right-of-way; and 2) when two aircraft are approaching head on, both aircraft should maneuver to their right. The current VFR rules of the road do not specify who has the right-of-way in an altitude conflict. Although some crews from the previous study suggested that the aircraft with a stable altitude should have right-of-way (Lozito, McGann, Mackintosh & Cashion, 1997), the crews were not provided with a rule for this case.

Scenarios

Each crew flew a total of eight different scenarios which ranged from 15 to 20 min in duration. Crews flew a low and high density version of four scenario types. The order of blocks (low vs. high density) was counterbalanced. The conflicts in the high and low density versions of each scenario type were identical, except different call signs were used and different levels of non-conflicting traffic were represented. The intruders in all of the scenarios intersected the ownship's flight path laterally. For all conflicts the ownship and intruder were initialized 12 min from the closest point of approach if no maneuvers were taken.

For three of the four scenarios the angle of intercept between the ownship and intruder aircraft was manipulated. In the acute angle scenario type, the intruder intersected the ownship's flight path at an acute angle (approximately 22°). In the right angle scenario type, the intruder crossed the ownship's flight path at a right angle (approximately 90°). In the obtuse angle scenario type, the intruder intersected the ownships path at an obtuse angle (approximately 165°). In all three of these scenario types, the ownship had the maneuvering responsibility (i.e., the intruder was on the right).

In the final scenario type, the intruder passed closely in front of the ownship (8-9 nm) but did not trigger any alert (Almost Intruder or AI scenario). The intruder was initialized to pass in front of the ownship at approximately 12 min from the start of the run. If no maneuvers were made in this scenario, the two aircraft would not have lost separation. In this scenario type, the ownship was on the left, and the intruder had maneuvering responsibility.

Due to the different conflict geometries and the 120 nm simulated ADS-B range, the intruder aircraft was not always depicted on the flight crew's navigation display from the start of each scenario. Specifically, it took 48 s from the start of the scenario for the intruder to appear on the navigation display in the right angle scenarios and 4 min 19 s into the obtuse angle scenarios. If either member of the flight crew reduced their navigation display range below 160 nm, the appearance of the intruder could have been delayed further. The intruder was always present on the navigation display in the acute angle and AI scenario at the 160 nm map range. For the controllers the conflicting aircraft always appeared on their display, but the aircraft did not necessarily originate within the controller's sector. However, at the start of each scenario, any traffic that appeared on the controller's screen and that would be in the controller's airspace at some time during the scenario was preselected for the controller. This meant that the controller had responsibility for those aircraft and was supposed to monitor their progress.

In order to increase the difficulty/workload of the scenarios an aircraft blocking the most common avoidance maneuver was included in each scenario. Previous full mission research on airborne self-separation found that a lateral maneuver directed behind the intruder aircraft was the most common conflict avoidance maneuver in lateral conflicts (Cashion et al., 1997; Johnson et al., 1997). Thus for each of the three conflict angle scenarios (acute, right and obtuse), a blocker aircraft flew a course parallel to the ownship approximately 10-12 nm off the right side of the ownship. In the

AI scenario, the blocker was located on the left side of the ownship at a similar distance.

Communications/Negotiations

Two confederates assisted in the communications and negotiations with the flight crews and controllers. The confederate pilots who represented the intruder and blocker aircraft were instructed to respond to calls from the flight crew and controller but not to initiate calls. The confederate pilot was instructed to maneuver if requested when the ownship had the right-of-way. When the intruder had the right-of-way, the confederate crew would maneuver if requested only after the second contact from the ownship. In addition, background communication was generated between the two confederate pilots and between one confederate pilot and the controller. Background communication consisted of requests for information such as turbulence reports, current flight parameters, and routing information. There were no air-to-air negotiations scripted into the background communications. The frequency congestion was equal for both traffic density conditions, about one call per minute.

Results

Safety

Self-separation

One measure of safety collected was the pilots' ability to maintain adequate separation between their aircraft and the other traffic. Pilots had self-separation authority until the Authority Transition point was reached, at which time the controller could intervene. Adequate separation was defined to the pilots as either 5 nm laterally or 2000 ft vertically, while for the controllers adequate separation was defined as either 5 nm laterally or 1000 ft vertically. The purpose of having different vertical separation minima for the flight crews and controllers was to provide a buffer and thus prevent the controller from intervening too early. It should also be noted that the airborne alerting logic used for this study was very prototypic. The conceptualization and the technical requirements necessary for airborne alerting logic is still ongoing. The self-separation data from the alerting logic used in this study should be interpreted with caution.

In four of the 80 runs, vertical separation of 2,000 feet was not maintained. Twice, separation was lost because crews who had climbed to avoid the conflict descended back to their optimum altitude too early. This occurred once in the low density, acute angle scenario where vertical separation was reduced to 933 ft before reaching 5 nm of lateral separation, and once in the low density, right angle scenario where vertical separation was reduced to 1,242 ft before reaching 5 nm laterally. In the remaining two cases, separation was lost because crews who had climbed to avoid the conflict did not reach 2,000 ft vertical separation before incurring the 5 nm lateral separation zone. This occurred once in the high density, obtuse angle scenario where the flight crew reached only 1679 ft vertically when within 5 nm of the intruder aircraft, and once in the high density, acute angle scenario where the flight crew reached only 1428 ft vertically when within 5 nm of the intruder aircraft.

Authority Transition

If an impending conflict was not resolved after an AZT, eventually the Authority Transition point was reached, which represented an even higher probability of conflict based on the airborne alerting logic. Procedurally, when the controllers received an Authority Transition alert on their displays, they were instructed to query the crews and could cancel free flight at their discretion. The Authority Transition alert was reached a total of six times in 80 runs. Four of these alerts occurred in the high density, acute angle scenario, and two occurred in the low density, acute angle scenario. Based on this alert, free flight was canceled by the controller once in the high density and once in the low density, acute angle scenario. In five of the six cases there was communication between the flight crew and the controller after the Authority Transition point. In the one remaining case, there was no communication between controller and flight crew after the Authority Transition alert. The flight crew had begun a descent, which perhaps mitigated the need for the controller to query the crew's intentions.

Additionally, two controllers cancelled free flight on their own initiative, before the Authority Transition point was reached. First, in a high density, right angle scenario, the controller felt that the crew's heading change was not sufficient to resolve the conflict and instructed the crew to descend 2,000 feet. The conflicting aircraft passed each other with 2,000 feet vertical separation, but only 4.03 nm of lateral separation. It is unclear if the crew would have increased the heading change to avoid a loss of lateral separation before the controller intervened with a descent. The second self-initiated controller cancellation of free flight occurred in a low density, right angle scenario, where again the crew's heading change appeared insufficient to the controller. The controller cancelled free flight on the intruder aircraft and instructed the intruder to turn left 10 degrees.

Finally, one flight crew requested cancellation of free flight on their initiative. This occurred in a low density, obtuse angle conflict. Although all controllers and pilots had been briefed that free flight eliminated any east/west altitude rule and that aircraft could fly at any altitude, this crew suggested that the intruder aircraft should maneuver because the intruder was "wrong altitude for direction." After requesting cancellation of free flight to the controller, the controller subsequently cancelled free flight on both aircraft and descended the intruder aircraft to resolve the conflict.

Lateral Separation

For those crews who resolved the conflict without using altitude (44% of all maneuvers), the mean lateral separation was examined for density and each conflict angle (see Table 1 for means and SDs). Because of the unequal number of lateral resolutions, no statistical analyses were conducted. In viewing the table of means, it is interesting to note that the acute angle conflict resulted in the smallest lateral separation distance from the intruder, almost always under 7 nm.

Detection Time

Flight Crew Conflict Detection Time

This analysis does not include flight crew detection of the Almost Intruder, which was detected by the crews as a potential conflict in all but one scenario. For the three planned conflicts, a collision would have resulted 12 min from the start of each scenario if no action was taken. However, because of the differing conflict geometries, the right angle and obtuse angle conflicts took 48 s and 4 min 19 s to come into the 120 nm ADS-B range on the pilots' navigation display. Thus, flight crew detection time was defined as the time it took for flight crews to detect the conflict after the intruder aircraft came into view on the pilots' display. These flight crew detection times were collected from the videotape data where two coders agreed that the flight crew

Table 1. Mean and Standard Deviations for Lateral Separation from Intruder Aircraft.

	High Density	SD		Low Density	SD	
Acute Angle	5.6 nm	0.4 nm	n=5	6.4 nm	1.2 nm	n=4
Right Angle	7.4 nm	0.9 nm	n=4	7.6 nm	2.7 nm	n=6
Obtuse Angle	14.6 nm	16.1 nm	n=5	8.6 nm	--	n=1

had verbally indicated the intruder aircraft was a potential conflict. A 2 (Density) x 3 (Conflict Angle) repeated measures Analysis of Variance (ANOVA) was conducted for flight crew detection time, and this analysis revealed a significant main effect for density ($F(1,7)=6.25$, $p<.05$, see Figure 7). Across the three conflict angles (acute, right and obtuse), crews took significantly longer to detect conflicts in the high density conditions as compared to the low density conditions (see Table 2 for means and SDs). It should be noted that crews nearly always (95% of the time) detected the intruder aircraft as a conflict before the airborne alerting logic was triggered. The conflict was detected by participant flight crews after the alert in only three runs, all of which were in the obtuse angle, high density condition.

Table 2. Mean and Standard Deviations for Flight Crew Conflict Detection Times.

	High Density	SD	Low Density	SD
Acute Angle	44.9s	64.0	14.4s	5.6s
Right Angle	42.4s	57.6s	33.0s	74.2s
Obtuse Angle	57.6s	50.5s	14.0s	15.1s
Overall	**48.3s***	**53.4s**	**20.7s***	**41.0s**

*$p<.05$

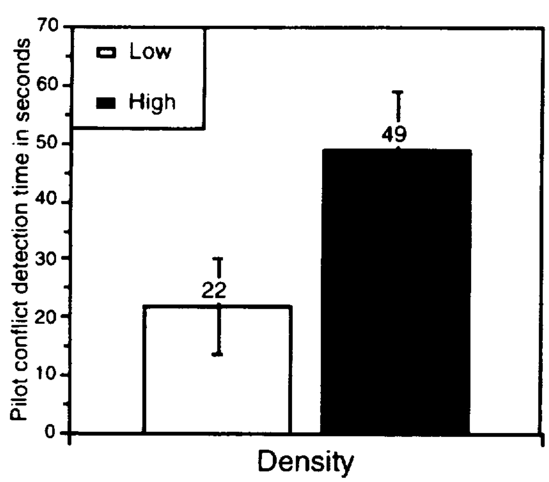

Figure 7. Pilot detection time for low and high density conditions (with ±1 standard error of measurement bars).

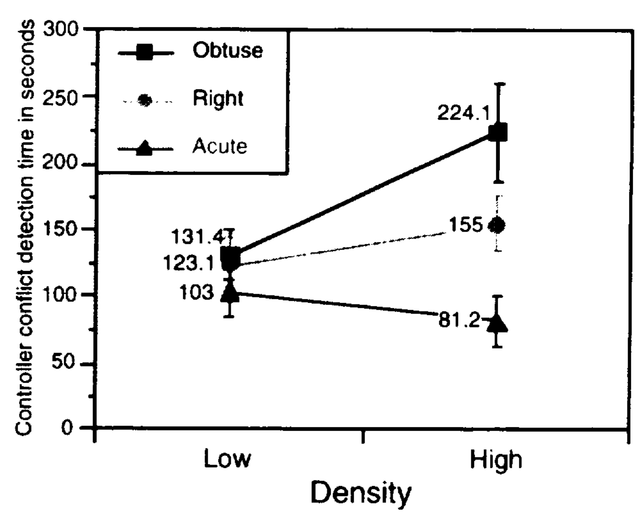

Figure 8. Controller dectection time for density and conflict angle (with ± 1 standard error of measurement bars).

Controller Conflict Detection Time

Controller detection time was defined as the number of seconds required for controllers to detect the conflict from the start of each scenario. (All aircraft were viewable to the controller from the start of each scenario.) A 2 (Density) x 3 (Conflict Angle) repeated measures ANOVA was conducted for controller detection time, and this analysis revealed a significant Density x Conflict Angle interaction ($F(2,12)=3.92$, $p<.05$, see Figure 8). Analyses of simple effects showed that controllers took significantly longer to detect the obtuse angle conflict in the high density condition as compared to the low density condition. Additionally, for conflicts in high traffic density, controllers detected the acute angle conflict significantly more quickly than either the right or obtuse angle conflict.

Aircraft Maneuvers

In three of the 80 runs, crews maneuvered because they assessed that the blocker aircraft was a threat. All three of these maneuvers for the blocker aircraft occurred in the obtuse angle conflict before the intruder aircraft came into view on the pilots' navigation displays. Thus, the three maneuvers for the blocker aircraft were dropped from the analyses of maneuvers taken to resolve the conflict with the intruder. Additionally, no crews maneuvered for the near conflict or Almost Intruder; therefore this scenario type is not included in the analyses of maneuvers.

Maneuver Time

Flight crew maneuver time was defined as the number of seconds required for flight crews to maneuver for the conflict after the intruder aircraft came into view on the pilots' navigation display. There were three instances in which the flight crews maneuvered for the blocker aircraft prior to the conflict with the intruder. Because of missing data due to these early maneuvers, separate t-tests were run for each conflict type to assess the effect of traffic density (see Table 3 for means and SDs). A significant effect for density was found for the obtuse angle conflict only, $t(7)=2.87$, $p<.05$, indicating that crews took significantly longer to initiate a maneuver in high traffic density as compared to low traffic density for the obtuse angle conflict (see Figure 9).

Table 3. Mean and Standard Deviation for Flight Crew Maneuver Times from Time Intruder is in View.

	High Density	SD	Low Density	SD
Acute Angle	183 s	55 s	129 s	32 s
Right Angle	136 s	62 s	143 s	151 s
Obtuse Angle	**170 s***	40 s	**125 s***	24 s

*$p<.05$

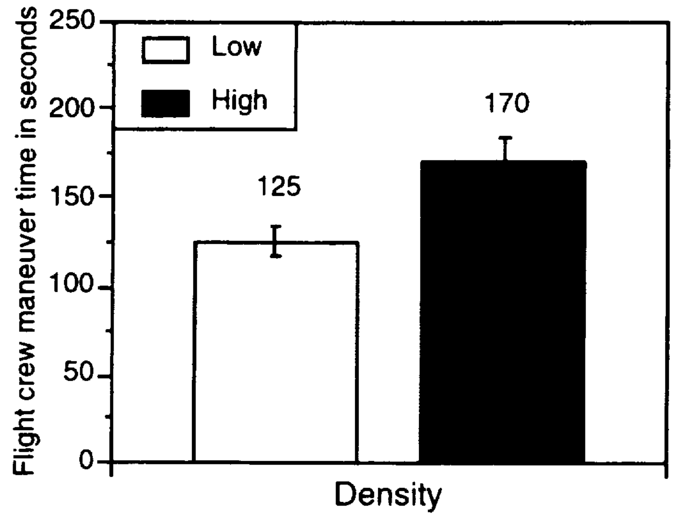

Figure 9. Mean flight crew maneuver times for obtuse conflict (with ± 1 standard error of measurement bars).

A similar analysis was conducted based on the timing of the maneuver relative to the flight crew alert (alert zone transgression). While there were no effects based on density, crews were significantly more likely to maneuver after the alert only in the obtuse angle conflict vs. prior to the alert for the acute and right angle conflicts, $\chi^2(2)=25.8$, $p<.001$, (see Table 4).

Table 4. Number of Crews Who Maneuvered Before or After Flight Crew Alert for Each Conflict Type.

	Before Alert	After Alert
Acute Angle	14	6
Right Angle	17	3
Obtuse Angle	1	16

Number of Parameters

Crews could use up to three parameters (speed, heading and/or altitude) to resolve a conflict. No effect for density was found. However, differences were found based on angle type and number of parameters used (see Table 5). Specifically, in the obtuse angle conflicts crews were significantly more likely to maneuver using one parameter (e.g. altitude), while in the acute and right conflicts crews were more likely to use 2-3 parameters. In all but two of the multi-parameter maneuvers, crews resorted to the second parameter after the first one didn't resolve the conflict alone (e.g., they waited one minute or more after enacting the first parameter to enact the second parameter). With both simultaneously initiated two-parameter maneuvers dropped from the analysis, the effect for conflict angle remains significant ($\chi^2(2)=7.05$, $p=.03$).

Parameter Type

Crews used speed, heading, altitude and combinations thereof to resolve conflicts. Across density and angle conditions crews used altitude 30 times, heading 27 times, and speed 19 times. No differences were found based on density or conflict angle.

Fuel Burn

The amount of fuel burned was collected for each run, and projected fuel burn to the next waypoint was calculated for each conflict type. No effects were found based on traffic density. Comparisons between the different conflict angles were not feasible because of different routes and distances to the next waypoint.

Table 5. Number of Parameters Used to Maneuver for Each Conflict Type (Simultaneously Initiated Maneuvers are Omitted).

	1 parameter	2 parameters	3 parameters
Acute Angle	11	8	1
Right Angle	12	8	0
Obtuse Angle	16	1	0

Use of Map Range

Separate 2 (Density) x 5 (Map Range) repeated measures ANOVAs were conducted comparing the total time spent at each map range (seconds) for each of the four conflict types. Because little or no time was spent at the 320 nm and 640 nm map ranges, these ranges were not included in the analyses. Thus, all analyses were conducted on the 10, 20, 40, 80, and 160 nm map ranges. Density x Range interactions were found for all scenario types [Acute, $F(4,76)=12.34$, $p<.001$; Right, $F(4,76)=10.21$, $p<.001$; Obtuse, $F(4,76)=18.91$, $p<.001$; and the Almost Intruder, $F(4,76)=9.11$, $p<.001$].

All four Density x Range interactions indicated that more time was spent at the larger 160 nm map range in low density conditions than in high density conditions. Conversely, across all scenario types, crews were more likely to reduce the map range to 80 nm in high density conditions compared to the low density conditions (see Figures 10a-d).

Analyses of Communication

Air-to-Air Communication

The intruder and blocker aircraft pilots were confederates of this study. Thus, only the initial contact of the blocker and intruder aircraft by the participant flight crews was included in this summary. Most crews contacted both the intruder and the blocker aircraft in the three conflict types. For 38 of the 46 (82%) runs in which the intruder was contacted, the communication occurred prior to any airborne alert. The intruder and blocker were rarely contacted in the near conflict scenario (see Table 6).

Air-to-Ground Communication

Crews contacted the controller, although not consistently. In the three conflict scenarios, the controller was contacted in 36 of 60 (60%) runs. In the Almost Intruder scenario, the controller was contacted on only two of 20 (10%) runs. No differences were found based on conflict angle or traffic density. When crews initiated communication it was usually to inform the controller of their maneuver taken to resolve the conflict. Interestingly, when the controller was informed by the crews, only 13% of the time did they report a specific parameter change prior to initiating their maneuver. Similarly, the controllers contacted the crews occasionally (20% of all runs), usually to query their intent or to point out other traffic in the vicinity.

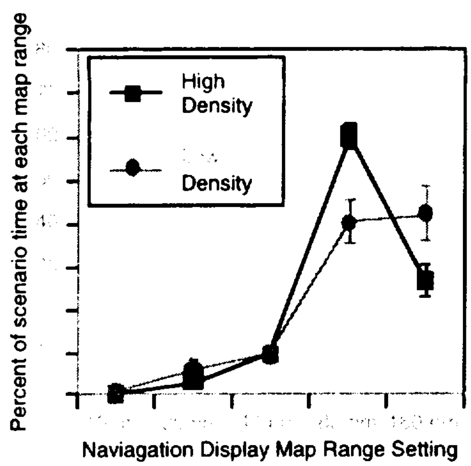

Figure 10(a). Traffic density by map range for right angle scenarios.

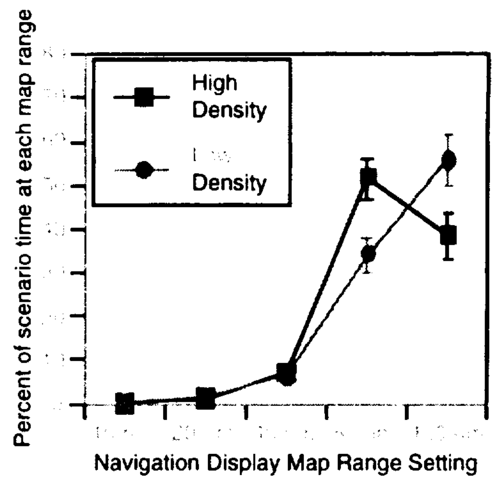

Figure 10(b). Traffic density by map range for acute angle scenarios.

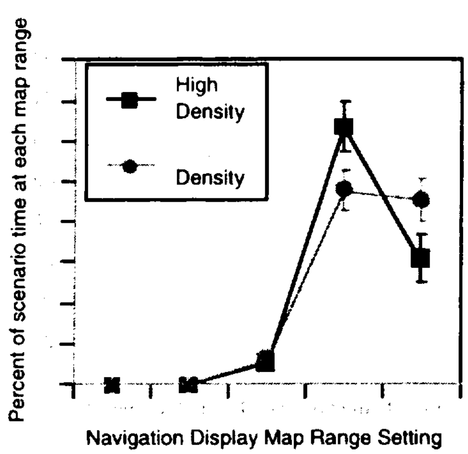

Figure 10(c). Traffic density by map range for obtuse angle scenarios.

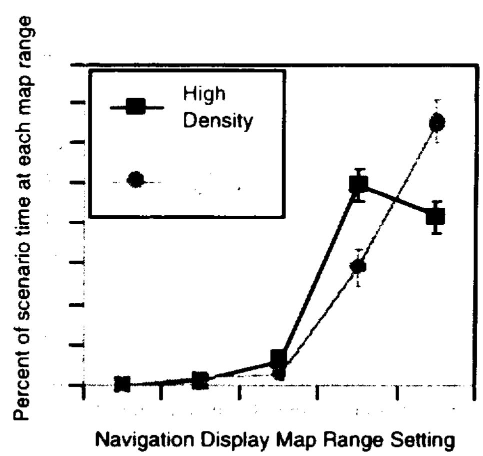

Figure 10(d). Traffic density by map range for almost intruder scenarios.

Table 6. Flight Crew Initiated Air-to-Air Communication.

	Acute Angle	Right Angle	Obtuse Angle	Almost Intruder
Contact Intruder	16 of 20 runs	15 of 20 runs	15 of 17 runs	4 of 20 runs
Contact Blocker	10 of 20 runs	14 of 20 runs	17 of 20 runs	4 of 20 runs

Subjective Ratings

Post-block questionnaires were administered to all participants after completion of the block of low density scenarios and after completion block of high density scenarios.

Flight crews

Based on the post-block questionnaire data, crews indicated some differences based on traffic density. Of the nine items on the flight crew questionnaire (see Appendix A), three items were scored as significantly different based on traffic density. First, crews rated the conflicts as more difficult to detect in high traffic density as compared to low traffic density, $t(19)=2.65$, $p<.05$, eta = .52. Second, crews indicated that they felt more time pressure in high density traffic scenarios, $t(19)=3.33$, $p<.01$, eta = .61. Finally, crews indicated that they felt a significant increase in workload in high traffic density when compared to low traffic density, $t(19)=2.85$, $p<.01$, eta = .55.

Controllers

As with the flight crews, the controllers also revealed some differences based on traffic density. Of the four items on the controller questionnaire (see Appendix B), three items were scored as significantly different based on traffic density. First, controllers rated the complexity of the traffic as greater in high traffic density relative to low traffic density, $t(9)=6.0$, $p<.001$, eta = .89. They also rated their workload as greater in high traffic density, $t(9)=6.09$, $p<.001$, eta = .89, and the task difficulty as greater in high traffic density, $t(9)=4.0$, $p<.01$, eta = .80. Unlike the pilots, the controllers did not indicate a difference in how difficult it was to detect a conflict based on traffic density.

It is interesting to note that the majority of the controller participants rated the high density traffic scenarios as only moderate workload relative to their everyday operations. When asked how much separation they would like to see between aircraft, the majority of the controller participants (80%) indicated that they felt comfortable with 7 nm or greater lateral separation, and/or 2,000 feet vertical separation. Additionally, controllers unanimously indicated that they would prefer pilots to check in with them *prior* to making any maneuver.

Discussion

The purpose of this study was to examine flight crew and controller human performance issues in a self-separation environment. Results indicate a number of interesting findings regarding how self-separation may impact safety, performance, communication, and workload.

Safety

One measure of safety collected was the maintenance of adequate separation between aircraft. Four of the 80 runs resulted in a loss of vertical separation. Twice, the lost separation occurred because crews who had climbed to avoid the conflict descended back to their original altitude too early. Similar maneuvers have been reported in previous flight deck studies (Cashion et al., 1997; Cashion & Lozito, 1999). The remaining two losses occurred when crews who had climbed to avoid the conflict did not reach the 2,000 ft vertical separation before incurring the 5 nm lateral separation zone. While a loss of adequate separation occurred in 5% of the simulation runs, these results should be interpreted with caution given the prototypic nature of the alerting logic.

Additionally, data were collected on the number of times the Authority Transition point was reached and the number of times free flight was cancelled. The Authority Transition alert was reached six times during the 80 runs. Based on the alert and the controller's assessment of the situation, free flight was canceled in two of these six runs. In addition to the cancellations initiated by the Authority Transition alert, two controllers cancelled free flight prior to the Authority Transition point, because they were not comfortable that the crew's maneuver was sufficient to resolve the conflict. Finally, one flight crew requested that the controller cancel free flight because they believed that the intruder aircraft should be required to maneuver. In the post-experiment questionnaires, controllers were asked if they had not been required to wait for the Authority Transition alert whether they would have cancelled free flight at any time during the scenarios. Interestingly, 60% of the controllers said that they would have cancelled free flight during the high density scenarios and 10% stated they would have cancelled free flight during the low density scenarios. This may indicate that some traffic configuration factors (e.g. density or convergence angles of conflicting aircraft) may affect separation distances desired by the controllers and these may not be represented in an airborne alerting logic. These discrepancies in the desired separation minima may lead to differing expectations for the transfer of control between air and ground.

Performance

Flight Crew

While previous research did not indicate performance differences between high and low traffic density conflict conditions (Lozito, et al., 1997), this study found several. Additionally, the results indicate performance differences related to the angle of the conflict. First, flight crews took significantly longer to detect conflicts in the high density conditions as compared to low density conditions. It should be noted however, that crews detected the conflict prior to the alert 95% of the time. Second, for the obtuse angle conflict, crews took significantly longer both to initiate a maneuver in high density traffic, and were more likely to maneuver after the alert. Finally, while no density effect was found relative to maneuvering time, crews were significantly more likely to maneuver using one parameter in the obtuse angle conflict compared to using multiple maneuvers to resolve the acute and right angle conflicts.

As mentioned earlier, an aircraft that blocked the most common avoidance maneuver was included in each scenario. The presence of this blocker aircraft may explain the density-related performance differences. Through examination of the communication data it was evident that the blocker aircraft did engage the consideration of most crews. Flight crews attended to the blocker either to determine its status as an intruder aircraft, or to assess possible maneuvers for resolution of the conflict situation. With the blocker aircraft diffusing the crews' attention, as well as impeding the most common escape maneuver, it appears that the blocker may have added the desired complexity. While the flight crews had the same number of opportunities to maneuver and resolve the conflict in the low and high density conditions, the added complexity of the blocker aircraft may have revealed potential workload differences between the two conditions.

Another possible explanation for these performance differences may be in the data associated with the use of map range. Replicating findings from the previous simulation (Cashion et al., 1997), results showed that pilots spent more time viewing a smaller map range (80 nm) in high density conditions compared to the low density conditions. Conversely, more time was spent at the larger 160 nm range in the low density conditions than in the high density conditions. Thus, flight crews appeared to be using the range selection on the navigation display as a filter for the density of traffic depicted on the display. Crews also could be using the display range as a means to focus their attention on more relevant aircraft. The reduced 80 nm range selection may have helped manage the clutter on the screen and provided a more detailed view of aircraft in close proximity; however, this smaller range reduces the opportunity to see traffic as early as possible because it no longer includes the 120 nm ADS-B range of traffic. Hence, the smaller map range may lead to later detection and less time to resolve the conflict. This may be of particular concern in some of the convergence angles in which there is less time between surveillance range and the closest point of approach. For example, the intruder aircraft in the obtuse angle did not appear on the ownship display until 4 min 19 s into the scenario. If the flight crew had reduced their navigation display to 80 nm, the time of appearance for the intruder aircraft would have been even later. This results in later detection of the potential conflict and in turn, less time to resolve the conflict. Accordingly, this observation may explain the findings that, in the obtuse angle scenarios, crews tended to maneuver after the alert and to use only a single parameter to maneuver clear of the conflict.

Controllers

Wyndemere (1996) suggests that conflict geometry may impact the complexity of the conflict. Specifically, conflicts with a small convergence angle between the ownship and intruder aircraft are the most complex conflicts to manage. Furthermore, 90° intercept conflicts were found to be the easiest to affect, with the complexity increasing again as the convergence angle increased to a head-on conflict. Analyses of the controller data revealed a significant interaction between traffic density and conflict angle. Controller participants took significantly longer to detect the obtuse angle conflict in the high density condition as compared to the low density condition. Additionally, the controllers detected the acute angle conflict significantly more quickly than either the right or obtuse angle conflict in the high density condition. This is similar to findings by Castaño and Parasuraman (1999), who found that in high density traffic scenarios, conflict angle and amount of intent information available on aircraft interacted to affect controller conflict detection times.

These results correspond to the findings of Remington et al. (in press), which state that wider angle conflicts are associated with longer detection times. Further, this previous research also provides one possible explanation for the density differences in controller conflict detection. Remington et al. (in press) suggest that the number of intervening targets between the two conflicting aircraft may mask the salience of the conflict. Wyndemere (1996) used controller ratings to determine levels of complexity for conflict angles and concluded that shallower angles have the greatest complexity because they result in a longer period of potential conflict and require action to be taken sooner. However, given that larger conflict angles have faster closure rates and appear to be more difficult for controllers to detect in a high density scenario, perhaps a more systematic study of angle complexity is required.

It is interesting to note that while the acute angle conflict was easiest for controllers to detect, it was not as easy for the flight crews to resolve. In their post-experiment questionnaires, the majority of controllers stated that they felt comfortable with a lateral separation requirement of 7 nm. However, resolutions for the acute angle conflict were almost always under 7 nm in lateral separation. Although this separation distance did not violate the required 5 nm separation standard, it was clear that this lateral separation was uncomfortable for a number of the controllers as evidenced by the questionnaire data and the two free flight cancellations prior to the Authority Transition point.

Communication

Air-to-air communication

Similar to the findings from the previous studies in both full mission (Lozito et al., 1997) and part task (Cashion & Lozito, 1999) environments, most crews contacted the intruder aircraft in the three planned conflicts. Specifically, the ownship contacted the intruder aircraft 81% of the time. Furthermore, for 38 of the 46 runs in which the intruder was contacted, the communication occurred prior to any airborne alert. Previous research (Cashion et al., 1997), which used a multi-stage alerting logic, found that crews who contacted the intruder did so before the first alert in only two of the 37 runs. It was concluded that the alerting logic, and/or display feature changes associated with it, may signal the beginning of the self-separation procedures for the flight crew. Instead of three levels of alerting used in previous research, only one alerting level existed in this study. Thus, crews had no warning prior to AZT in this study. The participant crews in this experiment did not wait until the AZT to start their self-separation procedures. The start of separation procedures appears to be related more closely to timing rather than display features associated with the alerting logic. These alerting logic differences may need to be examined further. While no density differences for communication were found, crews did contact the blocker aircraft 68% of the time. This finding implies a tendency for the ownship to contact aircraft that may be either in close proximity to the ownship or that may be limiting escape maneuvers. These indications of a high potential of inter-crew communication in the self-separation environment and the associated impact on frequency congestion will need to be addressed.

Air-to-ground communication

Flight crews contacted the controller 60% of the time in the three conflict scenarios. These communications were initiated by the flight crew and were usually to inform the controller of the maneuver they had already taken to resolve the conflict. Interestingly, in the post-experiment questionnaire, all ten controller participants stated that they would want to be informed of all maneuvers the flight crew was making, and would want to know prior to the crew initiating the maneuver. One controller commented, "A constantly changing picture that I can only analyze by my scan (as opposed to an aural cue) is too difficult for extended time periods." Another stated, "I may possess information that they do not, which might determine a better course of action." Again, these data may present frequency congestion concerns if the voice channel is used in a self-separation environment.

Workload

In the self-report questionnaires, given after each block of high and low density scenarios, both crews and controllers indicated an increased workload in the high density conditions over low density conditions. Counter to the findings of van Gent et al. (1998), flight crews stated that conflicts were more difficult to detect, that they felt more time pressure, and that they had an increased workload in the high traffic density conditions compared to the low density conditions. Overall, controller participants indicated that the high density scenarios were only of moderate difficulty. However, supporting the results of earlier studies (Endsley, 1997, Hilburn, Bakker, et al., 1997; Hilburn, Jorna, et al., 1997; Galster et al., 1998) controllers did give a significantly higher rating to traffic complexity, subjective workload, and task difficulty in the high density versus low density traffic conditions. Automated conflict detection aids are assumed to be necessary enabling technologies for transitioning towards a free flight environment (RTCA, 1995). However, one recent study found no effect on controller mental workload with the introduction of a prototypic ground conflict probe in a free flight scenario (Metzger, Galster, & Parasuraman, 1999), though other effects associated with the conflict probe were identified.

General Conclusions

This study was an early attempt of an integrated examination of flight crew and controller human performance issues in a self-separation environment. While this simulation resulted in a number of interesting findings, there remain several human factors concerns that were not addressed. First, the traffic conditions represented in this study did not include several elements that could add substantial complexity to the scenarios. These conditions include weather and winds, special use airspace, and abnormal situations such as aircraft or passenger problems. Several pilots commented that too much time was spent monitoring the navigation display for traffic conflicts and that they would not be able to be as vigilant under abnormal conditions. Second, all aircraft other than the ownship were confederates of the study. Consequently, issues related to air carrier differences and the process of negotiations between carriers could not be addressed. Third, controllers in the study performed a monitoring role and were limited as to the guidance and instruction that they could give crews. It was apparent that this role was difficult and a number of controllers noted how it impaired their scan or picture and increased their workload. Finally, flight crews and controllers have access to different sets of information. For example, in one scenario, the blocker aircraft was on arrival into Denver International Airport. For the controller, this information was available on the traffic display; however, for the flight crew to gain this same information the crew was required to contact either the blocker aircraft or the controller. In the discussion following the simulation, several controllers commented that, in this situation, they would have started the blocker aircraft down early for its descent, allowing the ownship to make only a minor maneuver off course to resolve the conflict. In this scenario, when the flight crew maneuvered for the intruder, 38% of crews made a lateral maneuver and 63% made an altitude change. These differences in pilot and controller conflict resolutions, given the particular information provided to each, need to be systematically examined. Similarly, other questions to be addressed include procedural issues for moving between constrained and unconstrained flight, and final responsibility for separation.

In conclusion, this research has provided insight into some important air-ground integration issues. Flight crew performance differences between high and low traffic density conditions were found in this study that were not realized in the previous studies (Cashion et al., 1997). The addition of the blocker aircraft to obstruct the most common maneuver and add complexity to the scenarios may be responsible for these density differences. Additionally, several conflict angle differences were uncovered. The acute angle conflicts were easier for controllers to detect, but were not as easy for the crews to resolve. Furthermore, although the obtuse angle conflicts were detected later by controllers, crews were able to adequately self-separate. These differences have implications for the operational setting and should be investigated further. Finally, both air-air and air-ground communication issues were revealed. The high frequency of air-to-air communications and the consequent impact on congestion remains a problem to be addressed. Regarding air-ground communications, timing and content of information relayed between the flight crew and controllers may be of particular concern. In sum, these results have helped define and describe some of the procedural concerns for flight crews and air traffic controllers in a self-separation environment.

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Appendix A. Flight Crew Post-block Questionnaire

Date:	Block Number:	Crew Position: Captain / First Officer

AATT3 Flight Crew Post Block Questionnaire

Please answer the following questions while considering the last 4 scenarios you just flew.

1) Overall, how useful was the display in helping you to separate your aircraft from other aircraft?

1	2	3	4	5
Not very useful		Moderately useful		Very useful

2) Overall, how useful was the alerting system in warning you about potential conflicts?

1	2	3	4	5
Not very useful		Moderately useful		Very useful

3) How useful were the temporal predictors in detecting potential conflicts?

1	2	3	4	5
Not very useful		Moderately useful		Very useful

4) How easy was it to detect a potential conflict prior to an alert?

1	2	3	4	5
Not very easy		Moderately easy		Very easy

5) How much time did the alerting system provide for crew decision making and negotiation with intruding aircraft?

1	2	3	4	5
Not enough time		Moderate amount of time		Plenty of time

6) Overall, how much time do you feel you spent viewing the Nav display?

1	2	3	4	5
Not a lot of time		Moderate amount of time		A lot of time

7) Overall, how much time pressure did you experience <u>before</u> an Alert?

1	2	3	4	5
Not a lot of pressure		Moderate pressure		A lot of pressure

8) Overall, how much time pressure did you experience <u>after</u> an Alert?

1	2	3	4	5
Not a lot of pressure		Moderate pressure		A lot of pressure

9) Overall, how much workload did you experience throughout the task?

1	2	3	4	5
Not a lot of workload		Moderate Amount of workload		A lot of workload

Please mark your response on the corresponding line.

10) What range was most useful for maintaining a general awareness of potential traffic conflicts?

_____ 10 nm   _____ 160 nm
_____ 20 nm   _____ 320 nm
_____ 40 nm   _____ 460 nm
_____ 80 nm   _____ 640 nm

11) What range was most useful for determining an avoidance maneuver?

_____ 10 nm   _____ 160 nm
_____ 20 nm   _____ 320 nm
_____ 40 nm   _____ 460 nm
_____ 80 nm   _____ 640 nm

Appendix B. Controller Post-block Questionnaire

CONTROLLER POST BLOCK QUESTIONNAIRE

Date:	**Block Number:**

1a. How would you rate the overall air traffic complexity of the last 4 scenarios? (Circle one).

1	2	3	4	5
Very Low Air Traffic Complexity		Moderate Air Traffic Complexity		Very High Air Traffic Complexity

1b. Please rank the following factors for their contribution to your sector complexity rating. Start with 1 as the most significant factor.

Factor	Rank
Aircraft Count (number of aircraft in your sector)	
Density (the spacing of aircraft in your sector)	
Traffic Flow with Respect to Sector Design	
Aircraft Proximity to Sector Boundaries	
Conflict Proximity to Sector Boundaries	
Merging Traffic Flows (i.e., climbers in an overflight stream, etc.)	
Closest Point of Approach	
Angles of Approach	
Crossing Altitude Profiles	
Performance Mix of Aircraft	
Speed Mix of Aircraft	

2. How would you rate your workload during the past 4 scenarios? (Circle one).

1	2	3	4	5
Very Low Workload		Moderate Workload		Very High Workload

Please explain any factors that contributed to your workload rating.

____

____

3. How would you rate the task difficulty during the past 4 scenarios? (Circle one).

1	2	3	4	5
Not Very Difficult		Moderately Difficult		Very Difficult

Please explain any factors that contributed to your task difficulty rating.

____

____

4. How easy was it to detect a potential conflict prior to an alert?

1	2	3	4	5
Not Very Easy		Moderately Easy		Very Easy

Please explain the reasons for your rating.

5. Would you suggest adding a controller at any time during these last 4 scenarios?

❑ Yes ❑ No

Please explain your answer.

6. Would you re-sector laterally based on the last 4 scenarios? Describe how.

7. Would you re-sector vertically based on the last 4 scenarios? Describe how.

8. Would you have cancelled free flight at any time during the last four scenarios, if you had not been constrained?

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13. ABSTRACT *(Maximum 200 words)*

The concept of "free flight" is intended to emphasize more flexibility for operators in the National Airspace System (RTCA, 1995). This may include the potential for aircraft self-separation. The purpose of this simulation was to begin examining some of the communication and procedural issues associated with self-separation in an integrated air-ground environment. Participants were 10 commercial U.S. flight crews who flew the B747-400 simulator and 10 Denver ARTCC controllers who monitored traffic in an ATC simulation. A prototypic airborne alerting logic and flight deck display features were designed to allow for increased traffic and maneuvering information. Eight different scenarios representing different conflict types were developed. The effects of traffic density (high and low) and different traffic convergence angles (obtuse, acute, and right) were assessed. Conflict detection times were found to be lower for the flight crews in low density compared to high density scenarios. For the controllers, an interaction between density and convergence angle was revealed. Analyses on the controller detection times found longer detection times in the obtuse high density compared to obtuse low density, as well as the shortest detection times in the high density acute angle condition. Maneuvering and communication events are summarized, and a discussion of future research issues is provided.

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